RST-1: SUCCESSFUL INTEGRATION OF COUNTERMEASURES INTO TMD TESTING

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Abstract

The evolution of Theater Missile Defense (TMD) systems requires testing against increasingly complex ballistic missile targets which provide the desired engagement parameters. The parameters of interest vary depending on the phase and maturity of the interceptor or sensor program. The Radar System Test-1 (RST-1) mission required a TMD target with specific characteristics of a Tactical Ballistic Missile (TBM) threat to collect data for assessing ground radar capability and its level of performance against countermeasures. The countermeasures included: a Simulated Tank Fragmentation Debris (STFD) payload and performance of exoatmospheric tumbling maneuvers of a single object and multiple objects. The flexible design of the Hera target system made it possible to have the countermeasures fully integrated, tested, and ready for flight within six months. Close coordination with the customers and users facilitated the six month response time and provided a mission which satisfied all user objectives.

Simple modifications to the existing Hera missile payload dispense electronics and the midcourse software sequencer were required to perform the RST-1 mission objectives. These design modifications and the testing performed to verify correct performance are described. Results comparing preflight predictions to actual flight data are presented. A brief overview of Hera capabilities is presented followed by a description of the RST-1 requirements, ground testing, and flight test results.

1.0 Introduction

To complete the development of advanced TMD sensor and interceptor programs and assure that these systems have the required efficacy against increasingly sophisticated threats, test missions must be conducted against TBM targets. The Hera target has designed-in flexibility to emulate the desired threat characteristics including the performance of stressing maneuvers and the dispense of countermeasures. The Hera target system was developed by Coleman Aerospace Company (CAC) under contract to SSDC. The Hera flexible design made possible the successful integration and test of the countermeasures in an extremely compressed schedule. From mission go-ahead to the initial flight date, the Hera RST-1 missile was ready for flight in six months. Existing features of Hera which were already developed, qualified, and flown were adaptable to the RST-1 requirements.

The RST-1 mission required Hera to provide specific characteristics of a TBM threat to collect data for assessing ground radar capability and its level of performance against countermeasures. Figure 1.0-1 shows the RST-1 mission profile. The countermeasures included an STFD payload, and performance of exoatmospheric tumbling maneuvers of a single object and multiple objects. Figure 1.0-2 shows the STFD approach.

The RST-1 flight test occurred Wednesday, October 9, 1996. It was the sixth consecutive successful launch and flight of a Hera target. Hera Flight 6 was launched from White Sands Missile Range (WSMR) LC94 on a north to south trajectory. The Hera target successfully accomplished all phases of the mission from launch through boost flight, midcourse flight, and exoatmospheric deployment of self-inflating Mylar balloons. All primary and secondary test objectives and success criteria were achieved. Successful completion of the RST-1 mission paves the way for future sensor and intercept tests against Hera TBM targets with countermeasures. Countermeasures

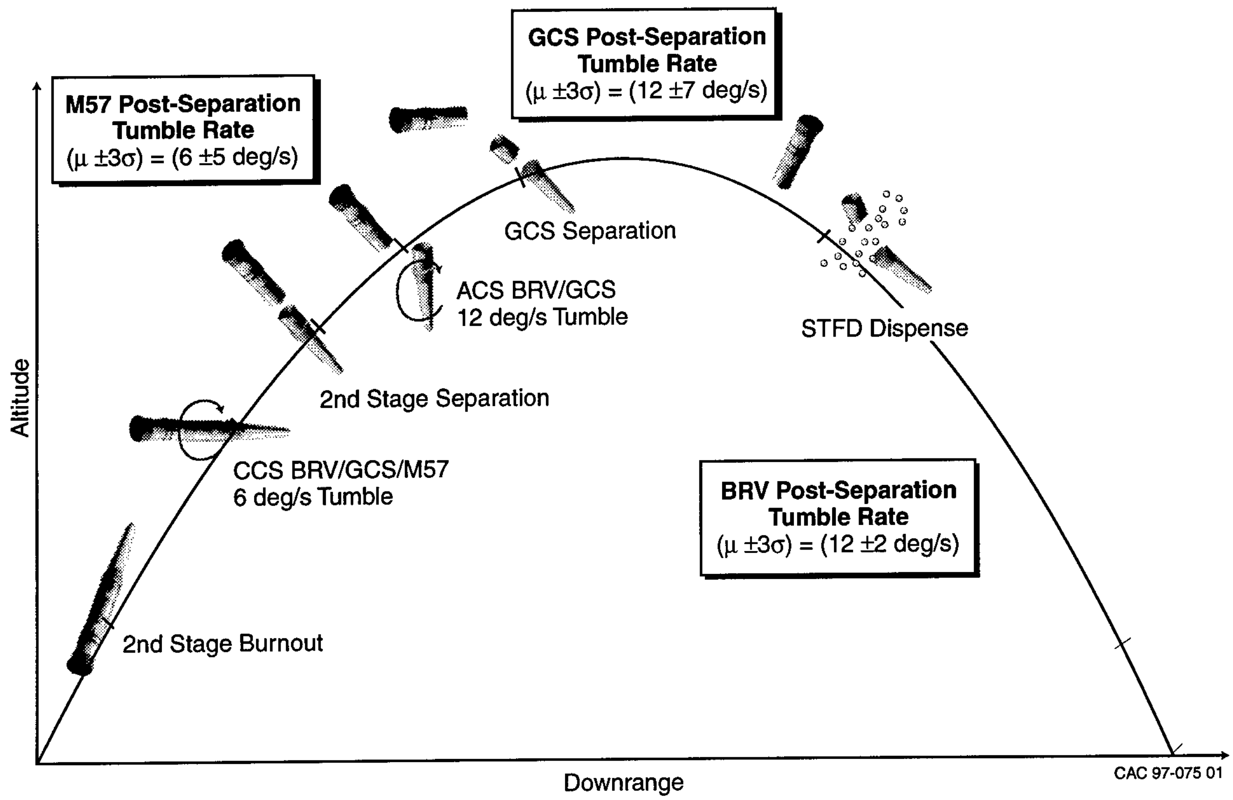
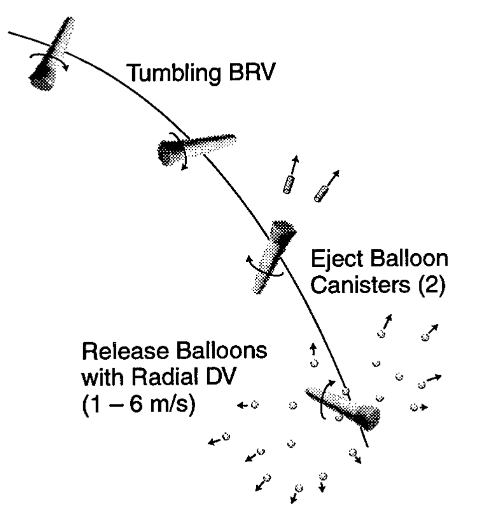


Figure 1.0-1. RST-1 Mission Profile



- Signal from TIRS to fire squib
- Canisters are ejected at 0.5 m/s
- Mechanical timer counts down time until balloon release (5s)
- Timer activates carbidge-tipped point to break glass and release balloons
- Balloons self-inflate with sublimating power
- Inflation force gives balloons a random, spherical velocity distribution
- Debris
  - Tiny pieces of glass
  - Canister end caps (two per canister)

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Figure 1.0-2. Simulated Tank Fragmentation Approach

capability, including carrying and dispensing penaids, now exists in all Hera targets.

1.1 Hera Capabilities

Hera provides ballistic or maneuvering trajectories over a 75- to 1,140-kilometers range with velocities between 1.5 and 3.0 kilometers per second. The software design allows for selecting a normal ballistic trajectory or extensive trajectory shaping (Pile Driver) by loading a set of software presets unique to the mission. The Hera apogee, range, and velocity/gamma requirements for conventional and Pile Driver missions are shown in Figure 1.1-1.

2.0 Hera Target Design

The Hera target design is modular and flexible to allow tailoring of missions for individual users by: 1) inclusion or deletion of specific hardware elements in the target; 2) test operation at a variety of test ranges with a minimum amount of facilities and support; 3) software selectable trajectories covering the spectrum of TMD threat kinematics; 4) tailored infrared (IR) and Radar Cross Section (RCS) signatures to match the desired threat characteristics; and 5) ballistic and maneuvering targets to replicate threat physical and material properties.

Figure 2.0-1 shows the Hera target system, consisting of the Target Air Vehicle Equipment (TAVE), Transporter/Erector (T/E), launch stool, Launch Operations Trailer (LOT), and Telemetry Ground Station (TGS).

2.1 TAVE

The TAVE consists of the Reentry Vehicle (RV), the booster stack, interstages, adapters, and guidance and control hardware. Figure 2.1-1 shows the Hera configurations which replicate the TMD threats. Hera provides a variety of ballistic targets and a maneuvering target for engagement and intercept either endoatmospherically or exoatmospherically. Countermeasures capability including dispense of penaids, maneuvers, and Electronic Countermeasure (ECM) packaging exists for the Hera target. These configurations allow a great deal of flexibility for the interceptor or sensor user program to define a particular test mission.

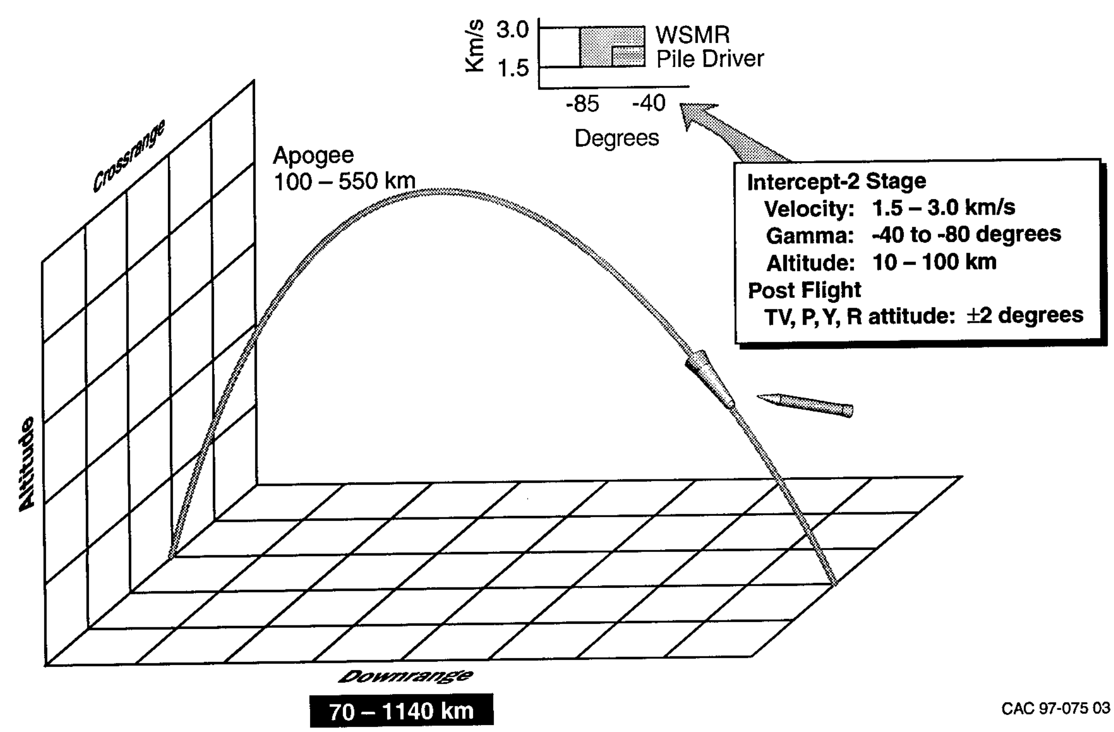

Figure 1.1-1. Hera Kinematic Requirements

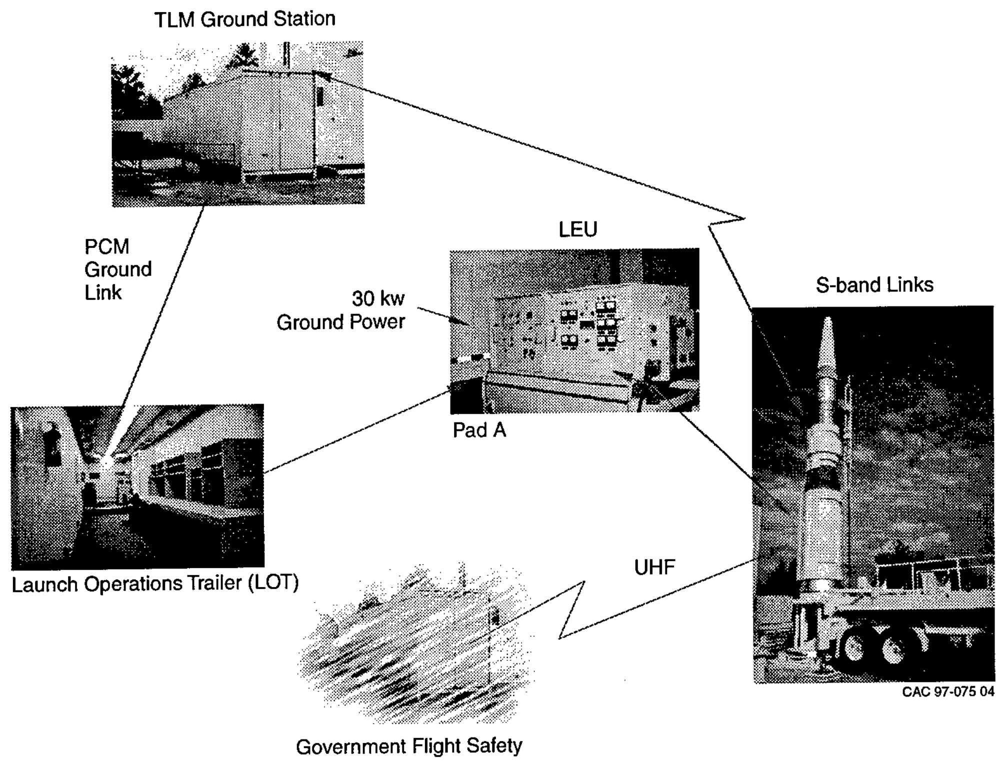

Figure 2.0-1. Hera System Launch Area Equipment

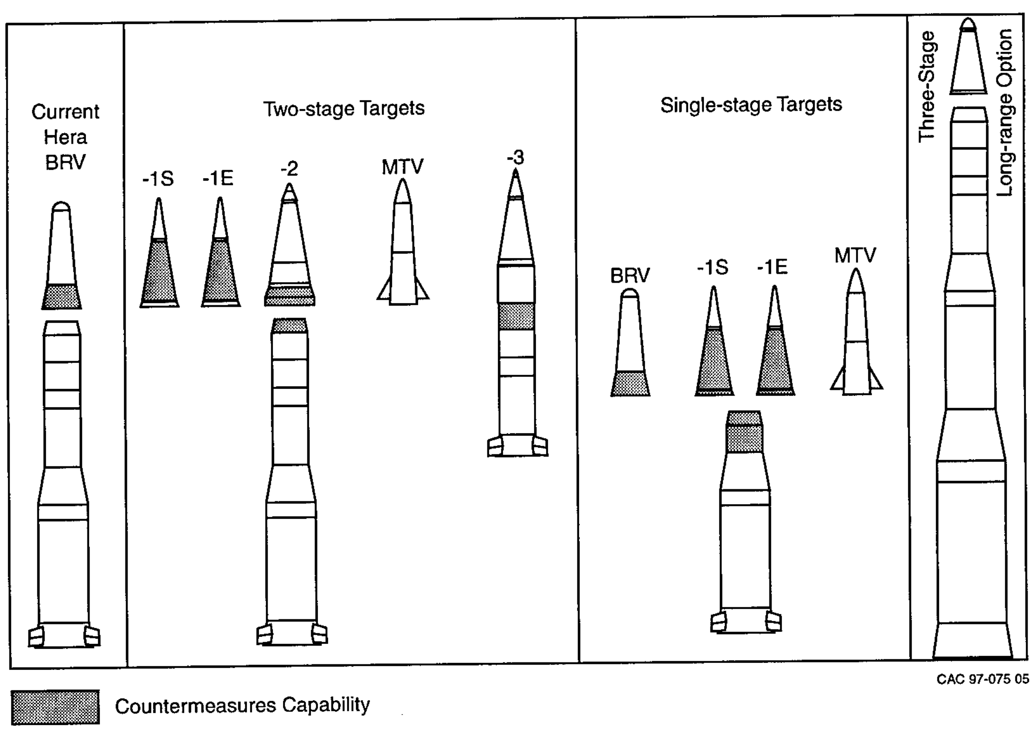

Figure 2.1-1. TMD Targets Family

2.2 Ground Equipment

Ground equipment required to check out and launch the Hera missile includes a T/E, LOT, generators, and a range safety van. These items are used for remote sites that do not possess blockhouses or commercial power. They contain all the necessary control panels, cabling, and launch computer hardware to count down and launch the target. The LOT hardware can be mounted in a blockhouse facility as is done for WSMR launches. Also available is a telemetry van that contains the recording and playback equipment.

2.3 Software

Hera flight software design is flexible and easily tailored via mission specific constants to satisfy a wide variety of specific trajectories. Through mission specific constants (presets) the flight and launcher software can be 'programmed' without modifying a single line of software to accommodate numerous missions and trajectories. Presets are constants that are loaded into memory after system power-up. Presets provides the following capabilities:

- Numerous two-stage separating and non-separating conventional and pile driver trajectories with various flight path angles and velocities
- Launch site location selection
- Missile aim point selection
- Guidance with or without thrust termination
- Energy management maneuvers
- Two-object threat object map [separating M57 stage relative to Guidance and Control Section (GCS) and Ballistic Reentry Vehicle (BRV)]
- BRV payload dispense at various altitudes
- Various modes of exoatmospheric missile control, Coast Control System (CCS), Attitude Control System (ACS) and rate versus attitude.

Substantial margins on memory and throughput and a flexible software design allow the addition of new capabilities without impacting existing functions. The software capabilities provide a quick response time and reliable software solution to mission requirements.

All Hera software is configured and controlled by the software development library in a software configuration management database. Software changes are authorized only by a Software Trouble Report (STR).

Airborne software is written in Bendix 930 assembly language, from the reuse of the Pershing II airborne computer. Approximately 90 percent of the Pershing II airborne code is being reused for Hera. The ground checkout and launch software is written in Ada for a 486 PC.

3.0 Hera RST-1 Design

Simple modifications to the existing Hera missile payload dispense electronics and the midcourse software sequencer were required to perform the RST-1 mission objectives. A new circuit card in the Payload Dispense Unit (PDU) was added to initiate or inhibit payload dispense of the balloon canisters. A Flight Termination Module (FTM) card was modified to create the STFD Dispense Unit (SDU) to safe and arm the canister eject ordnance. STFD canisters were added to the BRV, and networks were modified to supply the necessary signals to the new electronics. Software changes to the flight sequencer included the addition of the pitch tumble maneuvers and the canister eject commands.

The target hardware configuration summary for RST-1 is shown in Figure 3.0-1. In addition to the standard payload, water substituted for the bulk chemical simulant, the STFD package was carried as the secondary payload. The STFD package consisted of two L-Garde Multi-Balloon Canisters (MBCs). Each canister contained 50 self-inflating rectangular pillow-shaped Mylar balloons, each approximately 0.3 meters wide by 1.1 meters long when deployed.

4.0 Ground Integration and Test

A conservative mission success oriented test program philosophy has been adopted and proven to be beneficial to Hera. Key elements include comprehensive development tests (wind tunnel, ground vibration survey, and structural tests); subsystem environmental qualification tests; TAVE section-level environmental tests; an extensive software unit, integration and system level tests; and extensive system level tests, including complete end-to-end

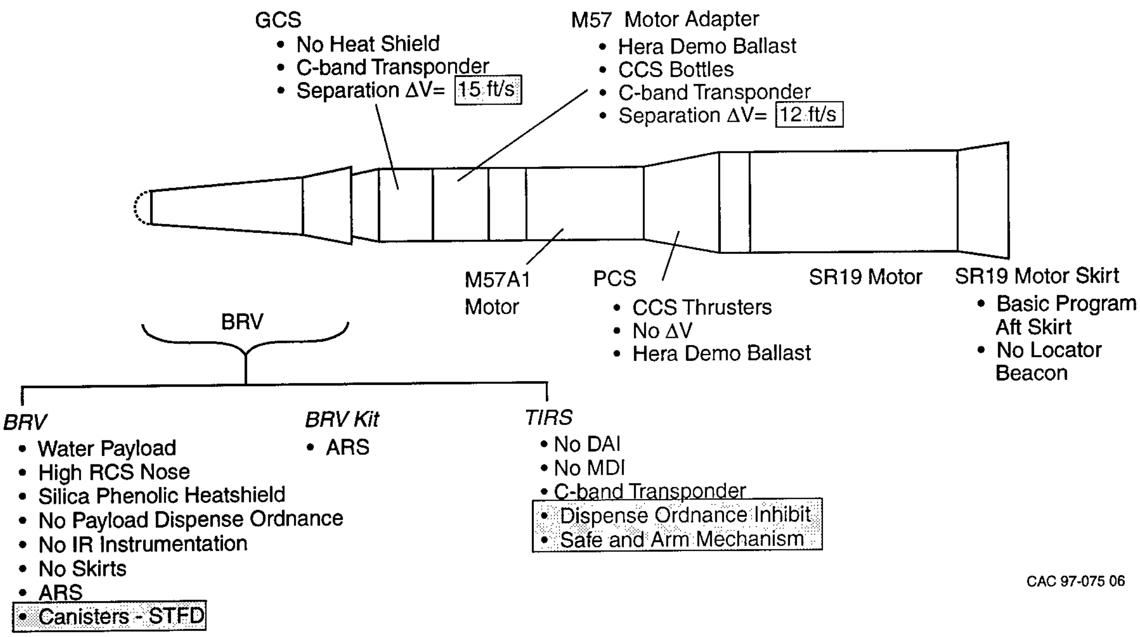

Figure 3.0-1. Hera RST-1 Configuration Summary

phasing, a live ordnance test, Computer-in-the-Loop (CIL), Hardware-in-the-Loop (HWIL), and range integration tests. An Engineering Test Missile (ETM) was built with fully functional hardware and inert motors to be used as a pathfinder for the CAC System Test Laboratory (STL). Hardware, software, and procedure problems were discovered early as a result of the ETM testing and subsequently corrected prior to flight tests. Table 4.0-1 summarize the Hera qualification tests and the risk mitigation approach.

4.1 RST-1 Ground Integration and Test

The existing robust design and rigorous testing methodology bound the additional tests for RST-1 to specific mission changes. The RST-1 test summary is as follows:

1) Engineering Development Tests
   - Aerotherm canister eject test
   - CRC verification of Integrated Electronics Unit/ Payload Dispense Unit (IEU/PDU) fire signal chain

2) Flight Hardware Integration and Acceptance Tests
   - PDU, SDU, Telemetry Instrumentation and Range Shelf (TIRS) Acceptance Test Procedure (ATP)
   - STL system-level tests through squib
   - WSMR Missile Assembly Building (MAB) integration tests with flight BRV and canisters

3) Qualification Plan
   - SDU – qualification by similarity to Flight Termination Module (FTM)
   - PDU – tactical qualification levels, agreed to by WSMR
   - Canister, ejector – qualification by similarity (flight qualified for MSX mission on a Minuteman Inter-Continental Ballistic Missile (ICBM). Balloons flown and dispensed on Red Tigress flight).

Engineering development tests included verification of the fire signal chain from the airborne computer through the canister squibs, and a canister ejection test. The canister ejection test verified proper function, ejection velocity, and interfaces. Because of an MBC balloon inflation temperature limitation of 100°F, thermal testing was also performed to establish a safety margin and to verify that the balloon inflatant would function properly in the ground handling, prelaunch, and flight environments for the mission. Flight hardware integration and acceptance tests were performed on the hardware with STL level tests through live squib firing.

Table 4.0-1. Qualification Tests

Test Article	Test Agency	Qualification Test Environments: Temp	Random Vibration	Sine Vibration	Shock	Acceler-ation	Thermal Vacuum	Status
BRV ETU-1-BCE with ordnance	Aerotherm	X	X	X	X			Complete
BRV ETU-2-BCE	Aerotherm	X	X	X	X			Complete
TM Signal Conditioner	SVC	X	X	X	X			Complete
IEU (less IMU)	CRC		X	X	X			Complete
PAC RAM PCB	CRC (Bendix)	X	X	X	X			Complete
IEU PCB (A28)	CRC	X						Complete
Rate Gyro Unit, 3-axis	CRC	S	S	X	X			Complete
Guidance Battery	CRC	X	S	X	S			Complete
MDI Electronics	CRC (Herley)	X	X	X	X			Complete
DAI Electronics	Kaman	X	X	X	X			Complete
Triplexer	CRC (FSY)		X	X	X			Complete
TIRS Power Distributor	CRC	X	X	X	X			Complete
ARS	CRC (ISI)	X	X	X	X			Complete
CHEFU	CRC	X	X	X	X	X	X	Complete
Flight Term Module	CRC	X	X	X	X	X	X	Complete
GCS and Motor Adapter Power Distributor	SVC	X	X	X	X			Complete
IEU PCB A29	CRC	X						Complete
IEU PCB A25	CRC	X						Complete
PCM and DAI Transmitters	CRC (Microcom)	X	X	X	X			Complete
PCM Encoder	CRC (Microcom)	X	X	X	X			Complete
FTS Battery	SVC	X	X	X	X	X	X	Complete
FTS Antenna/Coupler	SVC	X	X	X	X	X	X	Complete
Power Junction Box	SVC		X	X	X			Complete
Separation Initiators	SVC		X	X	X			Complete
TLM Battery	CRC	S	S	X	S			Complete
FTR	CRC (Vendor)	X	X	X	X	X	X	Complete
FTS Ordnance	SVC	X	X	X	X	X		Complete
Coast Control System	SVC	X	X	X	X			Complete
Signal Conditioning Assembly	CRC	X	X	X	X			Complete
Elevon Actuation System	CRC (Moog)	X	X		X			Complete

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All Block II Qualification Tests Completed Successfully

5.0 Flight Test Results

The RST-1 flight test occurred Wednesday, October 9, 1996. It was the sixth consecutive successful launch and flight of a Hera target. Hera Flight 6 was launched from WSMR LC94 on a north to south trajectory. The Hera target successfully accomplished all phases of the mission from launch through boost flight, midcourse flight, and exoatmospheric deployment of self-inflating Mylar balloons. All primary and secondary test objectives and success criteria were achieved as indicated in Table 5.0-1. All required telemetry and range tracking data were obtained. Figure 5.0-1 presents the trajectory overview.

Each of the flight phases—boost, midcourse, and terminal—were successfully completed with the actual achieved performance within the predicted envelope. During the boost phase, the first stage (a modified SR19-AJ1) and second stage (M57A1) successfully provided the necessary impulse to meet the requirements of a D-type trajectory. After first-stage burnout was detected, the second stage was successfully ignited. As in the previous Hera demonstration and Theater High Altitude Area Defense (THAAD) intercept missions, the Hera target did not thrust terminate (TT) the second stage booster. Figure 5.0-2 shows the boost guidance and autopilot timeline.

After second-stage burnout, the CCS successfully provided a six-degree per second controlled tumble of the unitary configuration (M57/GCS/BRV) which continued until second stage separation. Based on a preset timer designed to provide the desired attitude of the M57/GCS/BRV along the reentry velocity vector, the M57 separated after completion of one and one half revolutions of the unitary stack. The ACS then successfully provided a 12-degree per second controlled tumble of the GCS/BRV which continued until GCS separation. Based on another preset timer designed to provide the desired attitude of the GCS/BRV along the reentry velocity vector, the GCS separated after completion of two GCS/BRV revolutions. This provided the desired order of the objects: the BRV leading the GCS and the GCS leading the M57. After GCS separation, the three objects continued to tumble providing greater than 100 seconds of exoatmospheric observation time before the STFD dispense. At 408.7 seconds, MBC canister eject occurred. (Each canister contained 50 self-inflating rectangular pillow-shaped Mylar balloons.) After a five-second delay, the STFD balloons were dispensed. Optical coverage indicated that, following ejection,

Table 5.0-1. All RST-1 Objectives Successfully Accomplished

Objective	Success Criteria	Success (percent)
Primary Provide a short-medium range separating TMD target with specific characteristics of a tactical/Theater Balistic Missile (TBM) threat to collect data for assessing THAAD radar capability and level of performance against a) A single tumbling object b) Multiple tumbling objects with tumbling rates that are not necessarily the same c) Simulated Tank Fragmentation Debris (STFD)	1. Complete a conventional D trajectory with the following exoatmospheric maneuvers: a) Tumble unitary (M57/GCS/BRV) approximately one revolution at 6 deg/s b) Tumble GCS/BRV approximately two revolutions at 12 deg/s c) Separate GCS/BRV and dispense STFD post apogee 2. Obtain trajectory tracking and telemetry data to evaluate target performance using: a) Analog TM measurements b) Digital TM measurements c) Range tracking data	100%
Secondary Verify performance simulation	Obtain telemetry data for trajectory reconstruction	100%

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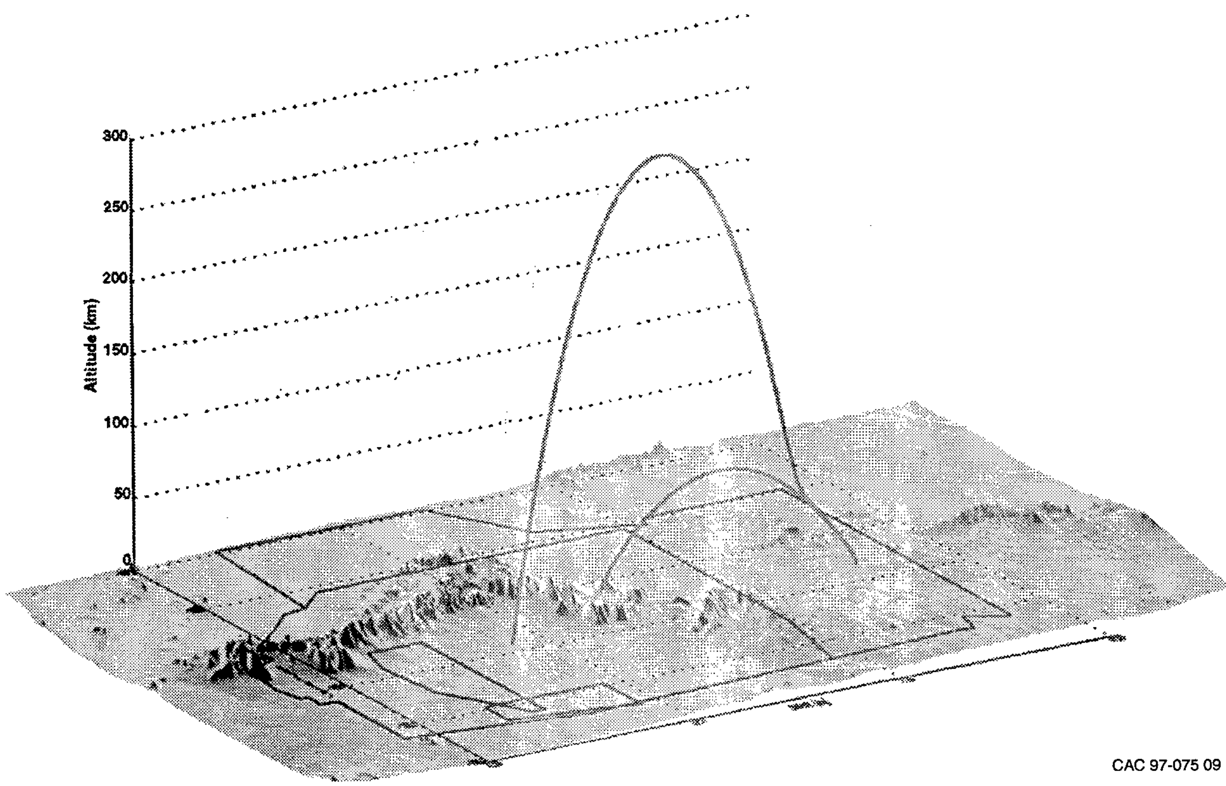

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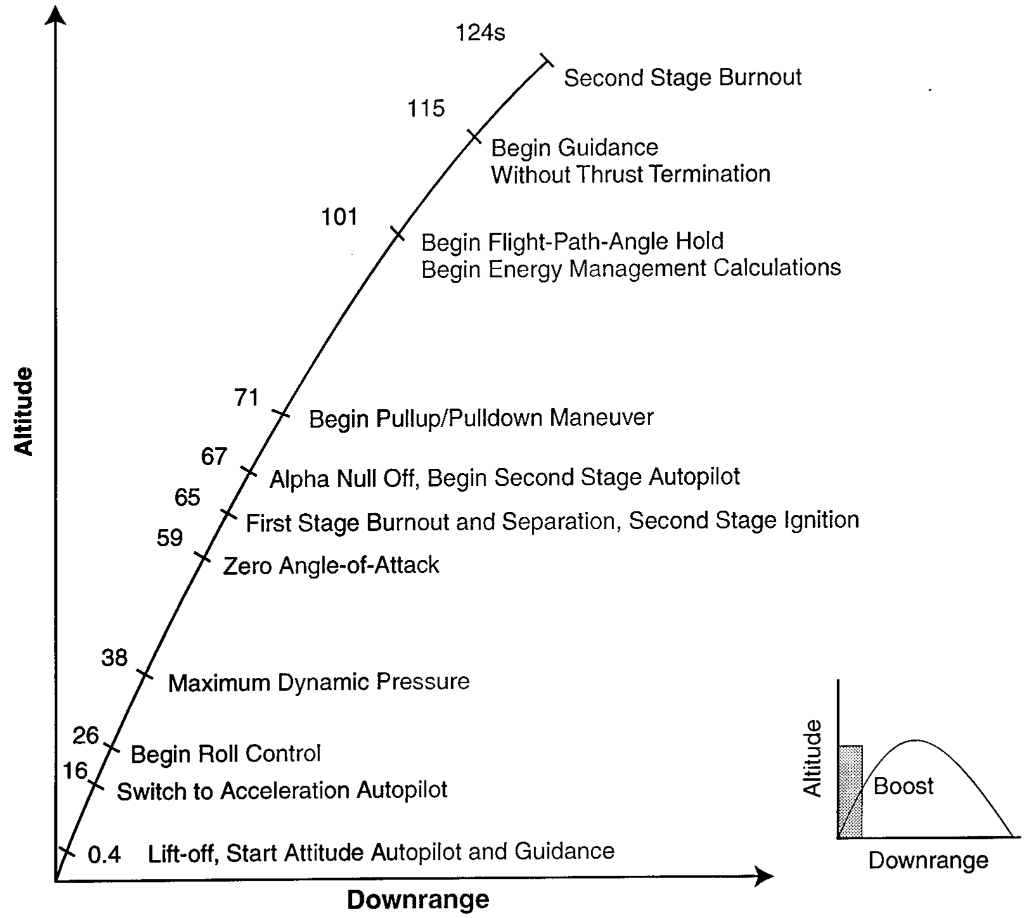
Figure 5.0-1. RST-1 Trajectory Overview



Event	Time (s)	Downrange (km)	Altitude (km)	Velocity (m/s)	Flight-Path Angle (deg)
FS Ignition	0.0	0.0	1.8	0.0	0.0
Liftoff	0.4	0.0	1.8	2.0	89.7
Switch to Accel A/P	15.6	0.1	2.9	173.0	83.4
Begin Roll Control	25.5	0.5	5.4	331.0	79.5
FS Alpha Null	58.7	6.3	25.7	1005.0	70.8
FS Burnout	64.6	8.4	31.7	1105.0	69.8
FS Sep/SS Ignition	64.7	8.4	31.7	1104.0	69.8
Alpha Null Off	66.8	9.2	34.0	1123.0	69.5
Begin Non-TT Guidance	114.8	24.3	99.1	1800.0	82.1
SS Burnout	124.1	26.5	116.6	1902.0	83.2

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Figure 5.0-2. RST-1 Boost Guidance and Autopilot Timeline (Nominal)

balloons were successfully deployed at the required time and altitude; thus, fulfilling the program objective of providing the required STFD. Greater than 100 seconds of exoatmospheric observation time of the BRV with dispensed debris was provided prior to reentry. The balloons were expected to deflate and burn up at reentry. Optical sensor report data from Optical Data Analysis (ODA) Development Center showed balloons were not visible at 578 seconds, which is about 40 kilometers in altitude. The target achieved the desired exoatmospheric discrimination time. The spent SR19 booster, M57 booster, GCS, and BRV ground impacts were all within performance predictions. Figure 5.0-3 shows the midcourse guidance and autopilot timeline.

5.1 Flight Test Data

The differences between the achieved trajectory and the preflight prediction fell within the expected tolerances. Figure 5.1-1 compares the achieved trajectory, as instrumented by the onboard inertial system, with the preflight simulation prediction. Trajectory data for the significant boost flight events are summarized in Figure 5.1-2.

Midcourse control system capability was upgraded for the RST-1 flight to include a pitch rate hold mode during any midcourse sequence. This functionality made it possible to successfully accomplish the unique requirements of the RST-1 mission to provide multiple tumbling objects with different tumble rates between the objects. Actual flight correlation to simulation was excellent. Figure 5.1-3 presents an overview of the midcourse performance relative to predictions. Figure 5.1-4 shows the Rate Gyro Unit (RGU) pitch rate flight data compared to the simulation.

5.2 Hardware Performance

Flight telemetry verified that the RST-1 electronics fire signal chain performed exactly as designed; the canister dispense command occurred exactly 200 seconds after the timer indicated it was running. The safe and arm electronics for the canister squibs was in a safe mode during the entire flight until one second prior to MBC eject. At one second before eject, the SDU armed. As designed, one second after the SDU was armed, the SDU applied three fire pulses (at one second intervals between pulses) to the MBC

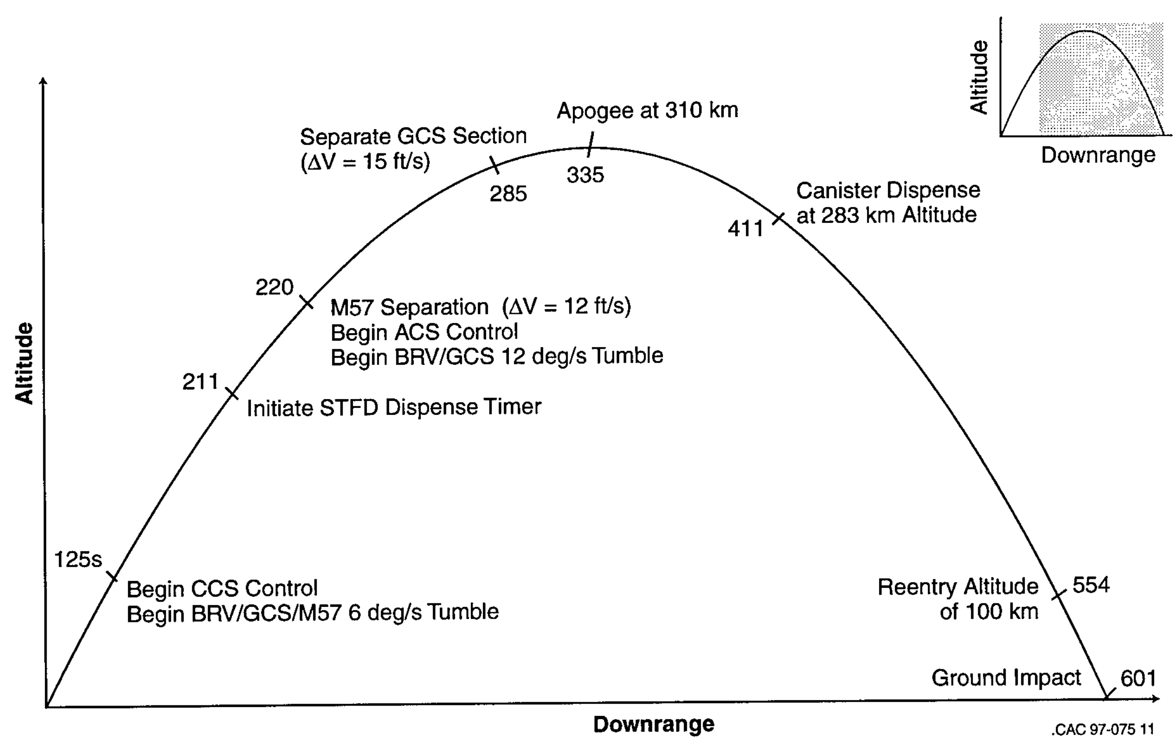


Figure 5.0-3. RST-1 Midcourse Guidance and Autopilot Timeline (Nominal)

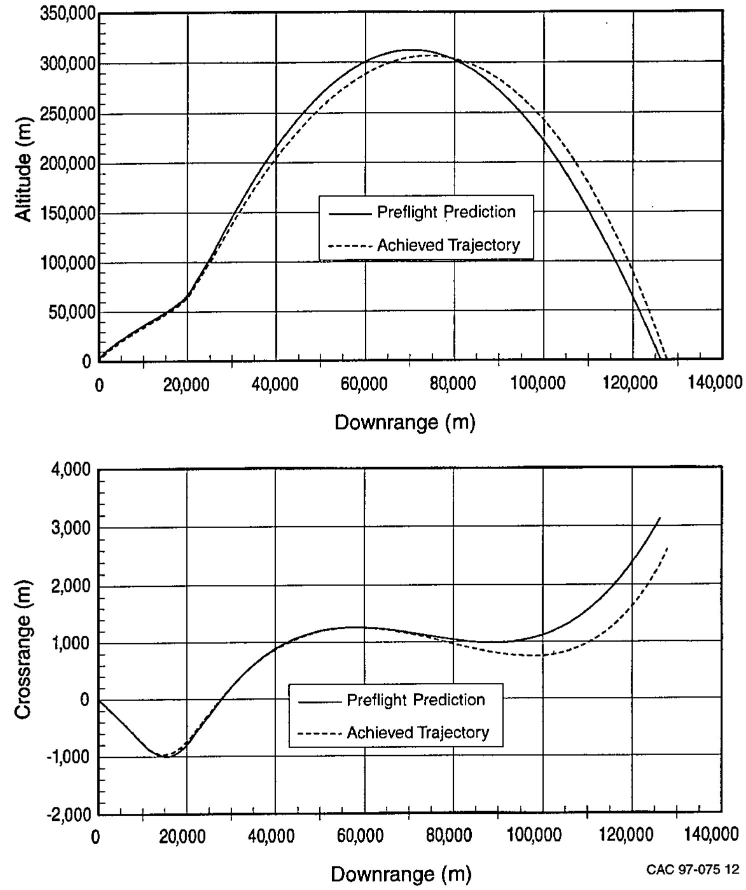
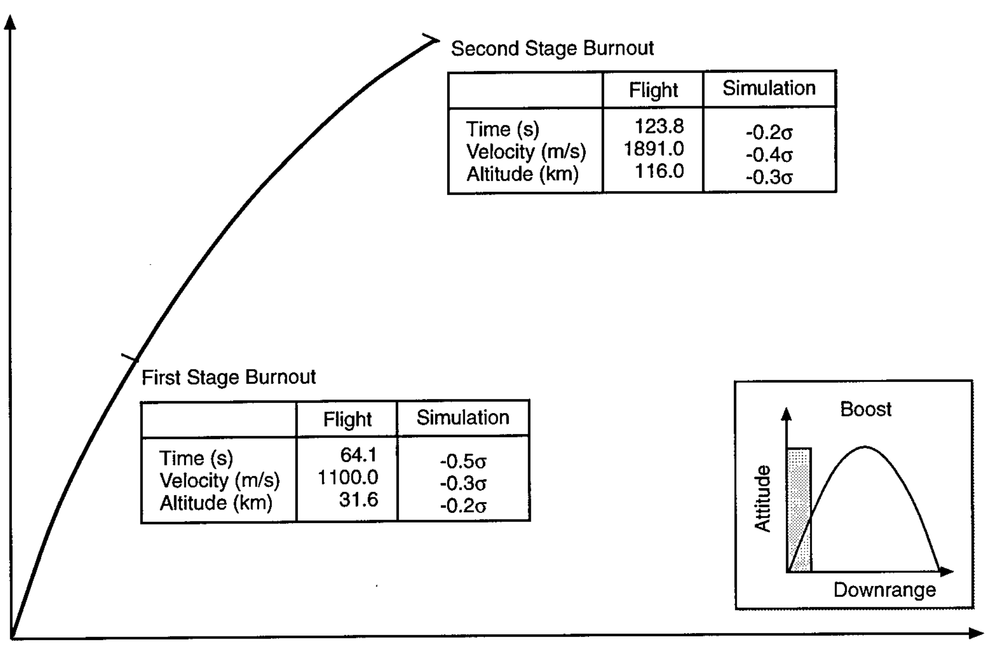


Figure 5.1-1. Comparison of Achieved Trajectory with Preflight Simulation Protection



Second Stage Burnout

	Flight	Simulation
Time (s) Velocity (m/s) Altitude (km)	123.8 1891.0 116.0	-0.2σ -0.4σ -0.3σ

First Stage Burnout

	Flight	Simulation
Time (s) Velocity (m/s) Altitude (km)	64.1 1100.0 31.6	-0.5σ -0.3σ -0.2σ

Statistics based on 100 run Monte Carlo set

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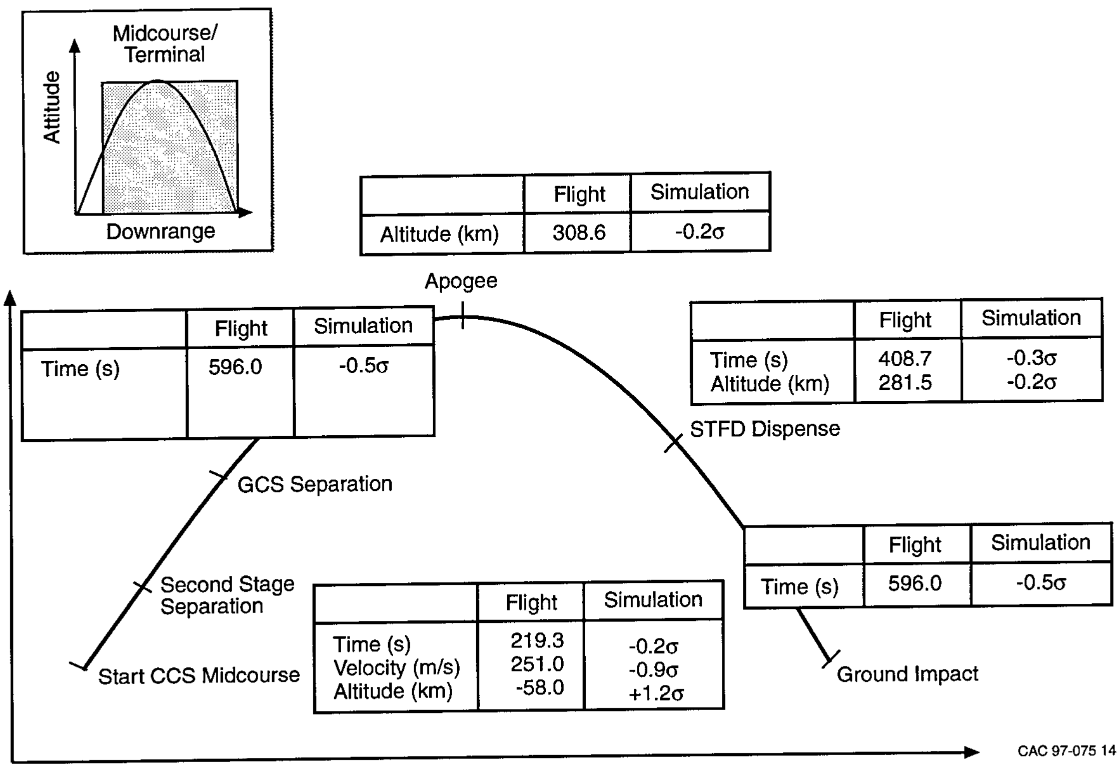
Figure 5.1-2. Overview of Flight 6 Boost Phase Performance



Statistics based on 100 run Monte Carlo set.

Figure 5.1-3. Overview of Flight 6 Midcourse Performance

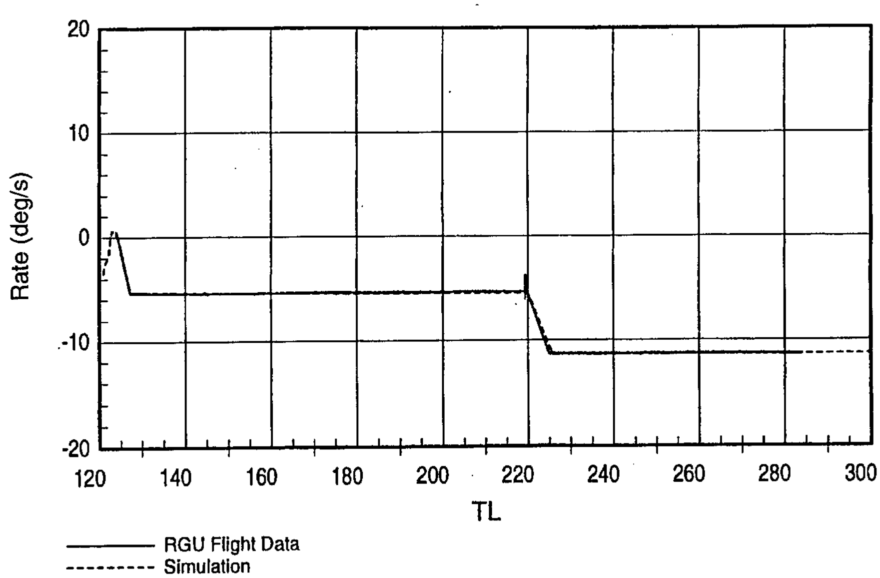


Figure 5.1-4a. RST-1 RGU Pitch Rate Compared to Simulation

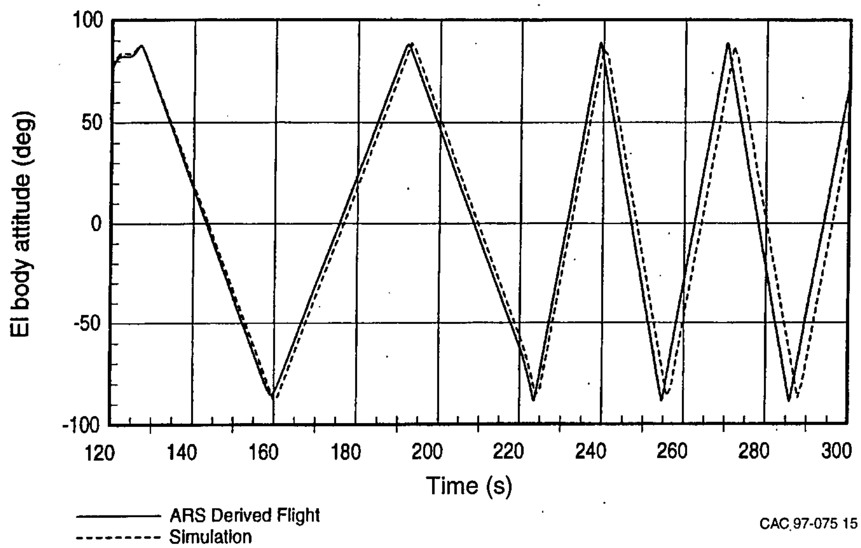


Figure 5.1-4b. RST-1 ARS Derived Pitch Attitude Compared to Simulation

ordnance. Radar coverage indicated ejection of at least one canister and deployment of the balloons after the preset five second delay.

6.0 Lessons Learned

The successful development and demonstration of the Hera countermeasures target provides some lessons which can be applied to other similar efforts. Some of these key Hera program development activities were: 1) extensive ground development testing; 2) high-fidelity simulation to predict flight performance; 3) extensive system integration testing using both pathfinder and flight hardware; and 4) extensive software testing including unit, integration, CIL and HWIL testing of the flight hardware and software.

One area requiring improvement was the ejection of the MBCs. Review of the 70 millimeter flight videos indicated that significantly less than the anticipated 100 balloons were visibly apparent. Target counts taken at different times and from different camera locations indicated a total field of 47 to 50 balloons, along with the three hard bodies and two smaller fragments, believed to be canister end caps or related canister debris, owing to their reduced signatures. Based on this data, and an anomalous MBC canister temperature measurement, it was concluded that one canister did not eject. Because of the redundant design of the electronics and the MBC canisters, the ejection of one canister and the deployment of 50 balloons ensured successful completion of all the RST-1 mission objectives.

After extensive failure analyses at all system levels, it was concluded that the root cause was a mechanical worst case tolerance problem in the MBC canister assembly. The design has since been revised to eliminate the error.

Well documented STL testing allowed the correct problem identification, which was a mechanical design error, not a squib firing circuit.

End-to-end ejection tests to verify deployment of the canisters, as well as additional telemetry instrumentation on the MBC to record ejection, are planned for any future missions.

7.0 Summary

The successful development and demonstration of countermeasures capability into the Hera TMD target resulted in a near perfect flight for the RST-1 radar test. The addition of countermeasures capability significantly expands the spectrum of TMD threats replicated by Hera.

Acronyms

ACS	Attitude Control System
ARS	Altitude Reference System
ATP	Acceptance Test Procedure
BCE	Bulk Chemical Experiment
BRV	Ballistic Reentry Vehicle
CAC	Coleman Aerospace Company
CCS	Coast Control System
CHEFU	Clocked High Energy Firing Unit
CIL	Computer-in-the Loop
DAI	Damage Asssesment Indicator
ECM	Electronic Countermeasure
ETM	Engineering Test Missile
ETU	Engineering Test Unit
FTM	Flight Termination Module
GCS	Guidance Control Section
HWIL	Hardware-in-the-Loop
ICBM	Intercontinental Ballistic Missile
IEU	Integrated Electronics Unit
IR	Infrared
LOT	Launch Operations Trailer
MAR	Missile Assembly Building
MBCs	Multi-Balloon Canisters
MDI	Miss Distance Indicator
ODA	Optical Data Analysis
PCB	Printed Circuit Board
PCS	Piledriver Control System
PDU	Payload Dispence Unit
RCS	Radar Cross Section
RGU	Rate Gyro Unit
RV	Reentry Vehicle
RST-1	Radar System Test-1
SDU	STFD Dispense Unit
STL	System Test Laboratory
STR	Software Trouble Report
STFD	Simulated Tank Fragmentation Debris
TAVE	Target Air Vehicle Equipment
TBM	Tactical Ballistic Missile
TGS	Telemetry Ground Station
THAAD	Theater High Altitude Area Defense
TIRS	Telemetry Instrumentation and Range Shelf
TMD	Theater Missile Defense
T/E	Transporter/Erector
TT	Thrust Terminate
WSMR	White Sands Missile Range